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UV GAS LASER INVESTIGATIONS

M. L. Bhaumik, et al

Northrop Research and Technology Center

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A peak laser power of 0.5 MW with an estimated efficiency of 0.2% has been obtained at 3577Å from a mixture of 92 psia Ar and 8 psia N_2 which was excited by an E-beam of 400A/cm^2 at 1.3 MeV in a 20 ns pulse. A saturation intensity of ~100 kW/cm^2 was deduced and a beam divergence of 10 milliradian was measured from the laser having a 10 cm gain length.

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UV GAS LASER INVESTIGATIONS

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1.0 SUMMARY

The overall goal of this program is to develop high efficiency, short wavelength lasers capable of high power operation. As a part of these objectives, a high power xenon excimer laser operating in the vacuum UV with reasonably high efficiency was developed. The results and conclusions of these investigations were reported in two previous semiannual reports[1,2] as well as in two published papers.[3,4]

In the current reporting period, emphasis was placed on the study of the newly discovered Ar-N_2 transfer laser. So far, a peak laser power of 0.5 MW with an estimated efficiency of 0.2% has been obtained at 3577Å from a mixture of 92 psia Ar and 8 psia N_2, which was excited by an E-beam of 400A/cm^2 at 1.3 MeV in a 20 ns pulse. A saturation intensity of ~100 kW/cm^2 was deduced and a beam divergence of 10 milliradian was measured from the laser having a 10 cm gain length. The higher saturation intensity is believed to be the result of removing the "bottlenecking" from the terminal laser state by fast collisional depopulation at the high pressures.

The details of the experiments and results are described in the following section. They are also incorporated in a paper accepted for publication in the IEEE Journal of Quantum Electronics; a copy of the paper is attached as Appendix I.

2.0 RESULTS AND DISCUSSIONS

The achievement of high efficiency rare gas excimer lasers has demonstrated the importance of these excimers for efficiently converting electrical energy into radiation at short wavelengths. Analytical investigations indicate that due to some uniquely favorable kinetic processes, the rare gas excimers may be capable of electrical conversion efficiencies up to 50%. However, the radiation from the rare gas excimers occurs only in the VUV region of the spectrum. Although high energy lasers in these wavelengths are important for some special applications, it would be more desirable to obtain high efficiency lasers in the transmissive region of the atmosphere since it would lead to more versatile applications.

The high conversion efficiency of the rare gas excimers may be successfully employed to develop visible and near UV lasers by using suitable energy transfer schemes. The possibility of such schemes was recently demonstrated[5] by a group of workers at the Stanford Research Institute. These investigators observed that electrical energy efficiency absorbed by Ar can be transferred nonradiatively to N_2 and NO with a high efficiency.

Based on these principles, S. K. Searles[6] at NRL built an Ar-N_2 laser with a mixture of 700 torr of Ar and 30-100 torr of N_2 excited by a 480 kV, 20 kA E-beam of 45 ns FWHM. Laser emission in the N_2 second positive band was inferred from a disproportionate increase in intensity along the optical axis when both cavity mirrors were employed compared to that observed with only the output mirror. Additional evidence was indicated by the fact that the emission with both cavity mirrors consisted only of the 3577Å line while the fluorescence emission consisted of lines at 3371Å, 3577Å, and 3804Å. However, the peak laser power was observed to be rather modest, between 10-100W.

A parallel investigation of the Ar-N_2 laser was initiated at Northrop employing the experimental setup used for the xenon laser. Although initial output powers were also modest, the investigations at Northrop have now demonstrated that the Ar-N_2 laser is indeed capable of high power with reasonably high efficiency. A laser output power of 0.5 MW with an efficiency of $\sim$0.2% has already been achieved at the 3577Å line of N_2. The details of the experiment and the results are described below.

2.1 Experimental Arrangements and Procedure. The experimental arrangement is schematically shown in Figure 1. A high pressure gas cell was excited transversely through a 1 mil thick titanium window. The gas cell contained two uncoated MgF_2 windows along the optical axis. One of the windows formed the output coupler for the optical resonator. The uncoated window is capable of approximately 2.5% reflection per surface. The resonator was completed with a 4 meter total Al reflector with a reflectivity of 92%. The resonator was aligned with a He-Ne laser.

The electron gun used to excite the high pressure gas cell was a Physics International Pulserad 110A. The output of the gun was 20 kA at ~1 MeV in a 20 ns pulse over an area of cross section 2 cm x 10 cm. Although the maximum E-gun current density was nearly 1 kA/cm^2, the effective current density inside the evacuated gas cell after traversing 4 mils of titanium and 1 cm of air, was 500A/cm^2. When the cell was pressurized, the current density was decreased further, along the E-beam direction due to scattering by the gas. The current density, which is an important parameter in establishing the laser threshold, was varied by placing additional scattering foil between the E-gun anode foil and the gas cell. The diode voltage was also varied over the range of 1.3 to 1 MeV. The volume of the excited gas was 2 cm x 2 cm x 10 cm. Due to an aperture of 2 cm diameter perpendicular to the optical axis, the laser extraction occurred from a volume of 30 c.c.

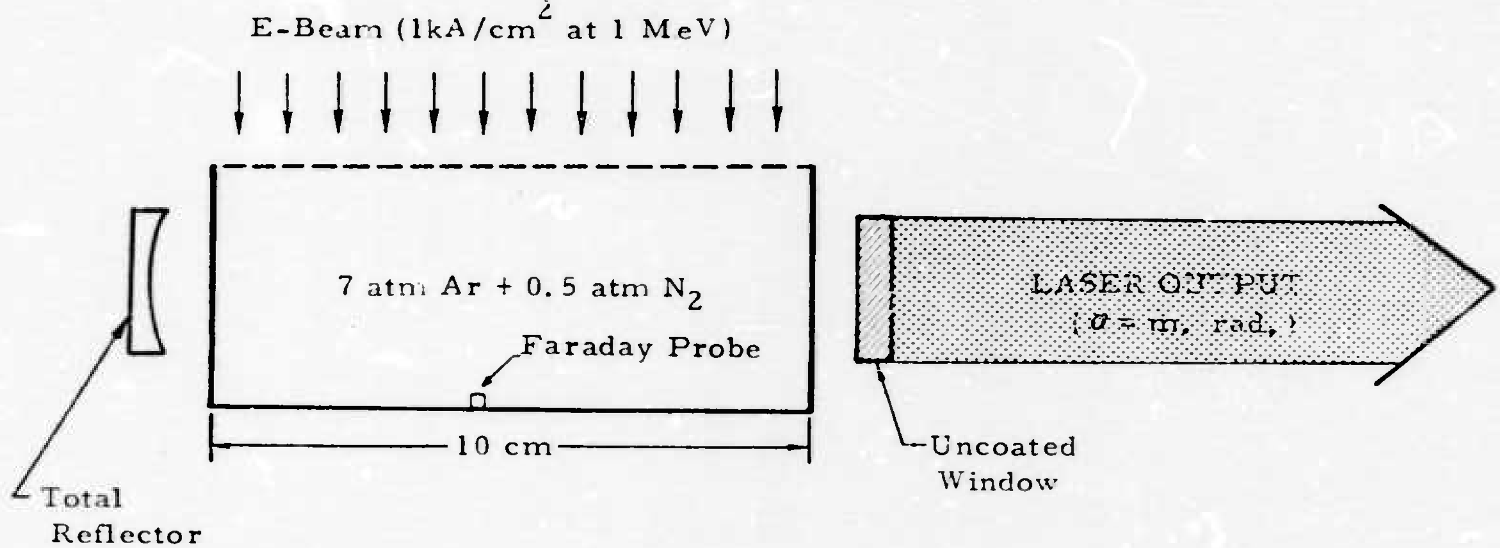


Figure 1. Schematic of the Ar-N_2 Transfer Laser.

Attempts were made to maintain the gas purity by carefully pumping all gas containers including the laser cell to a background pressure of 2×10^{-5} torr. The gases were pressurized in a separate container before filling the laser cell. In most cases the gas mixture was replaced after several shots. The purity of the filling gas was 99.99%.

The laser diagnostics were primarily accomplished by intensity measurements with an ITT FW 114A photodiode. A search was made for nonlinear buildup of intensity with temporal narrowing, an important proof of laser oscillation. The photodiode signal was measured with a Tektronix 7904 oscilloscope having a 500 MHz vertical amplifier. The direct optical pulse saturated the photodiode and therefore it was necessary to decrease the input intensity. In order to avoid the uncertainty in absorption coefficient of optical attenuators, especially at high intensities, a geometric attenuation technique was utilized. The technique, schematically shown in Figure 2, was simply to scatter the optical pulse by a MgO surface while positioning the photodiode at various distances from this surface.

The gas cell current density was monitored, simultaneously with the optical intensity, by means of a Faraday probe mounted flush with the rear surface of the gas cell. Spectral measurements of the laser output were made with a SPEX 1800 1 meter Czerny-Turner spectrograph having a dispersion of nearly 10A/mm. The spectral output could be detected either by a photodiode or by recording on film. The laser output energy was measured by a Gentek model ED200 calorimeter.

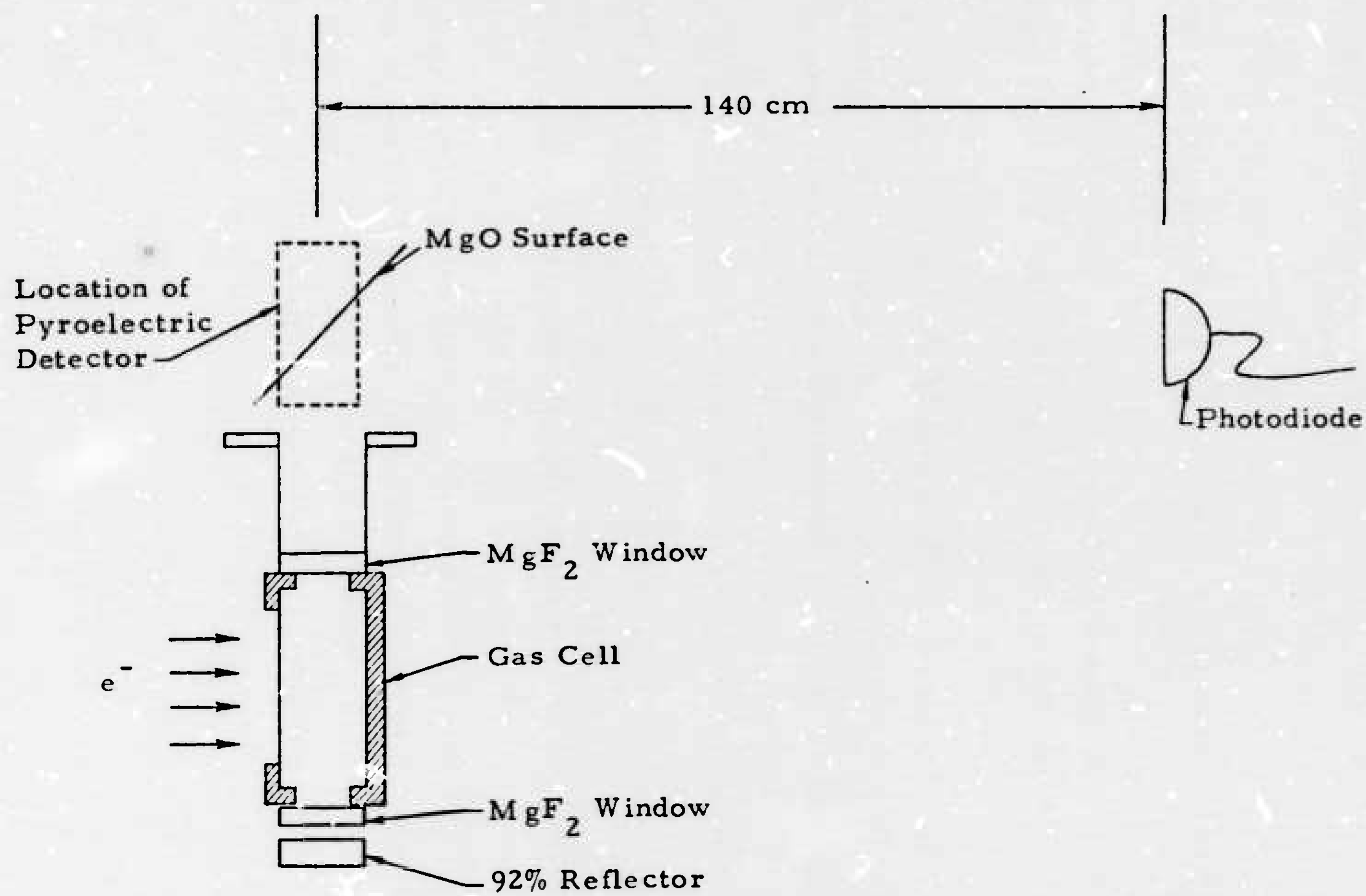


Figure 2. Schematic of the power and energy measurements of the $Ar-N_2$ laser. For energy measurements, the MgO surface was replaced by a pyroelectric calorimeter.

2.2 Results of the Ar-N2 Laser Experiments. The photodiode signals from an excited gas mixture of 16 atm Ar and 1 atm N_2 at three different current densities are shown in Figure 3. At a current density of $\sim 100 A/cm^2$ shown in Figure 3a, the threshold of the laser buildup is indicated by the intensity ripple on top of the fluorescence emission curve. By increasing the current density 30%, a disporportionate increase in intensity is observed, as shown in Figure 3b. By a further increase in current density of only 8%, a highly nonlinear buildup of intensity, characteristic of laser oscillations, is clearly demonstrated in the trace of Figure 3c. The temporal narrowing of the optical pulse is evident from Figure 4, which shows an optical pulse of ~8 ns FWHM with a rise time of 2 ns, while the E-beam current pulse is of a width of ~20 ns (FWHM) and a rise time of ~5 ns. The normal fluorescence pulse, not shown in the figure, follows the shape of the current pulse. Further evidence of the laser oscillations was provided by the optical intensity with and without the total reflector. The laser buildup disappeared when the total reflector was removed. Similar effects were observed when the cavity was misaligned.

The characteristic laser threshold effects are also clearly demonstrated in Figure 5, which shows the peak photodiode voltage as a function of peak Faraday probe current. The gas mixture for this set of data was 92 psia Ar and 8 psia N_2. As can be seen in the graph, the optical output increases by two orders of magnitude by merely doubling the current density. This can occur only due to laser oscillations. The laser intensity is also observed to reach a saturation at an intensity of ~300 kW.

The total energy output of the laser, as measured by the calorimeter, for the condition of maximum current density is shown in Figure 6. The highest energy measured was 4 mJ, which corresponds to a peak power of 500 kW for a pulse of 8 ns (FWHM). This peak power is consistent with the photodiode response after corrections to the geometric attenuation.

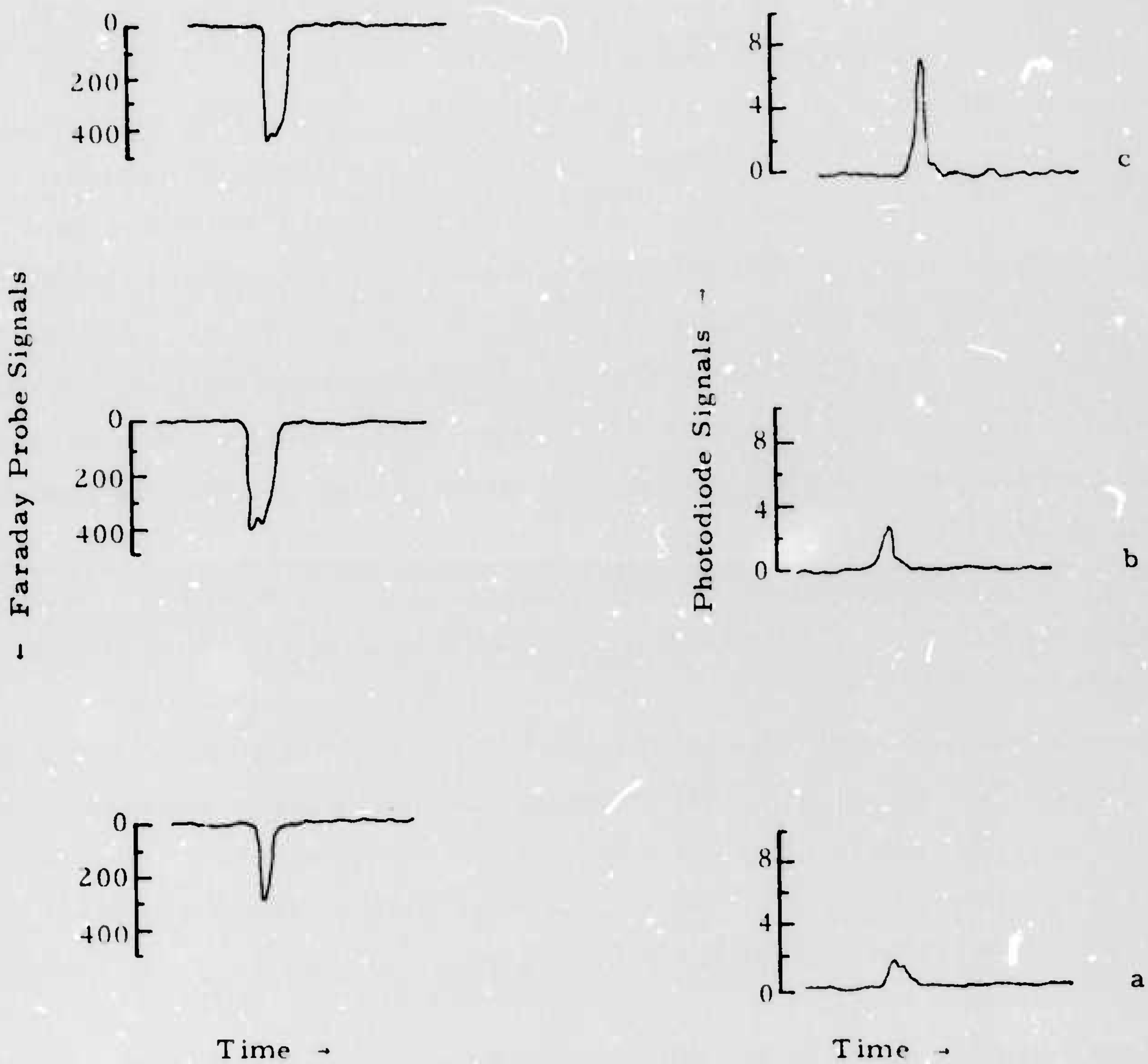
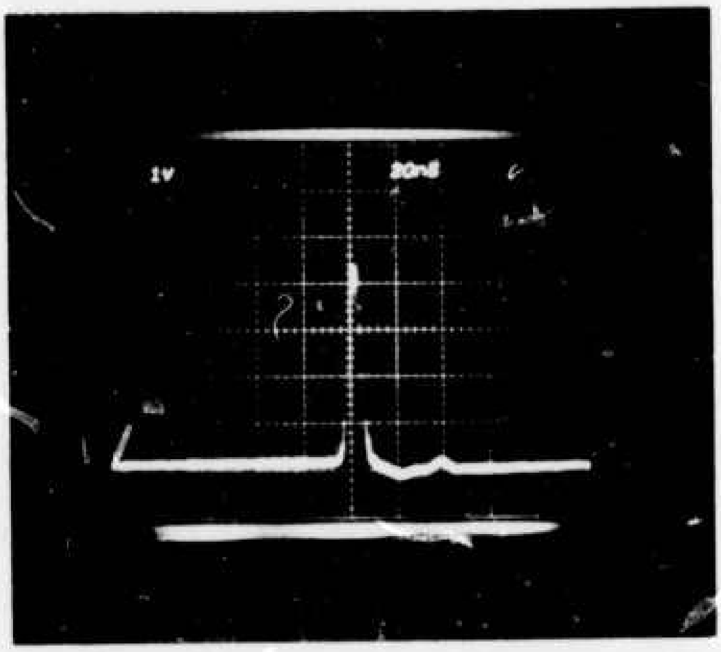


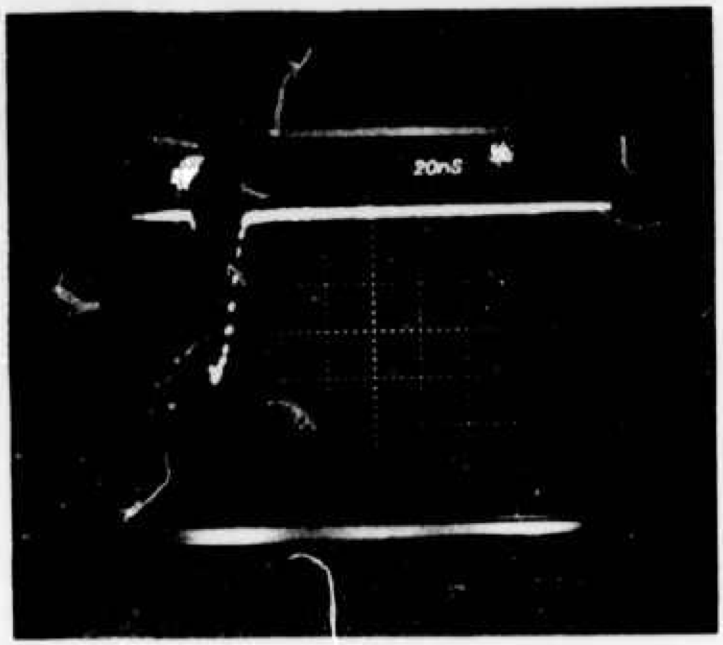
Figure 3. The photodiode output signals as a function of excitation current density near threshold.



≈120 kW/div.

Laser Output

20 ns/div.
(60 ns cable delay)



5 amp/div.

Faraday Cup
Signal
(Area = 0.075 cm^2)

20 ns/div.

Figure 4. Oscilloscope traces showing the Ar-N_2 laser pulse and the corresponding excitation current pulse.

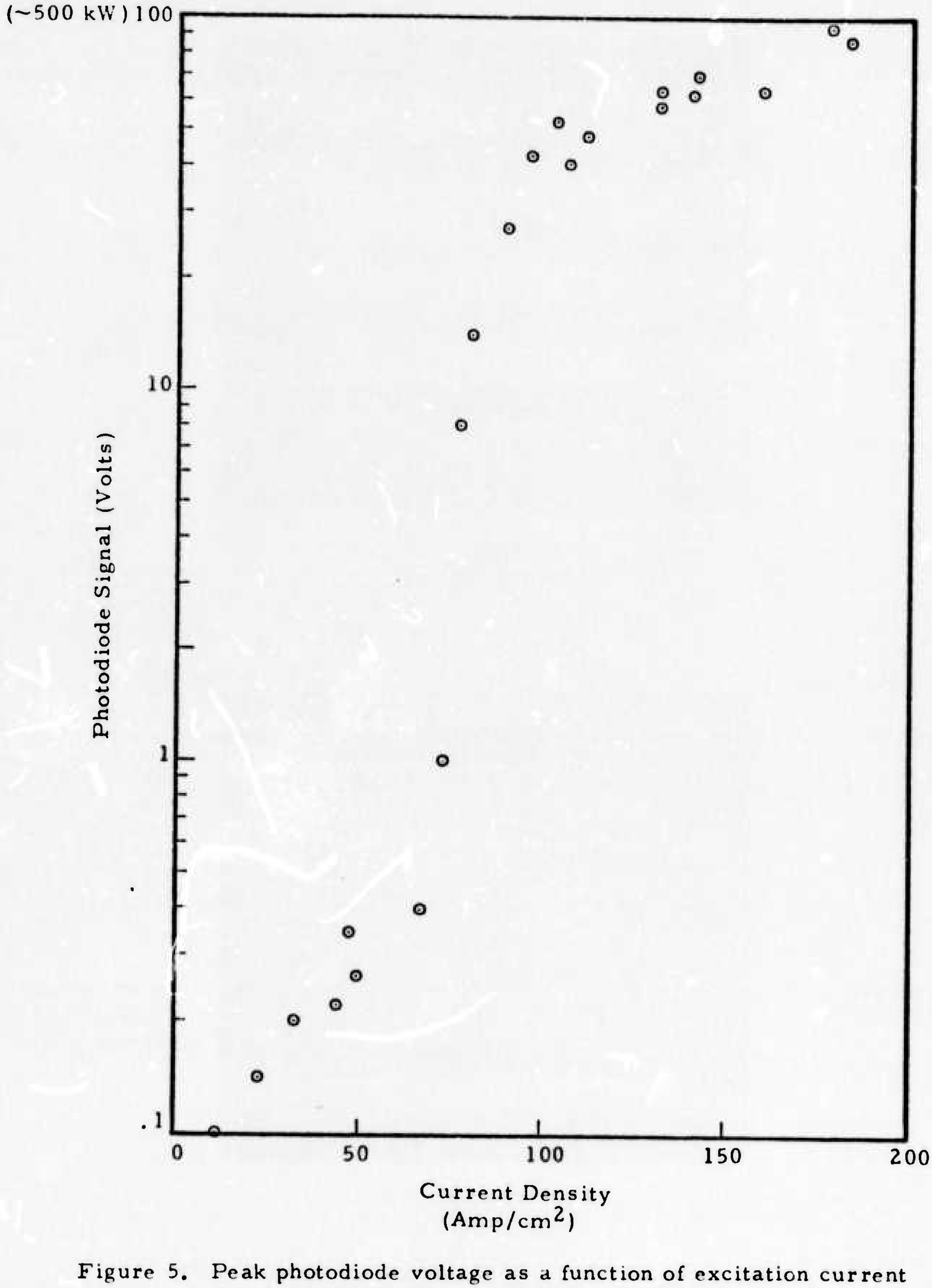


Figure 5. Peak photodiode voltage as a function of excitation current density showing laser threshold in a mixture of 92 psia Ar + 8 psia N_2.

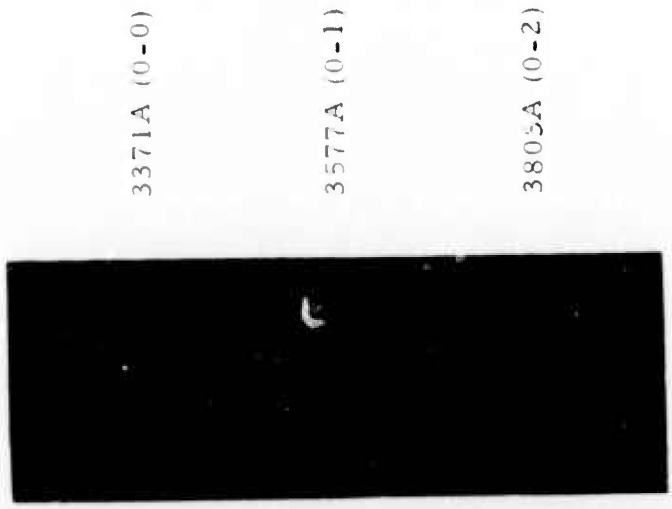
Figure 6. Response of the pyroelectric calorimeter; the width of the pulse is 50 ms which is the thermal relaxation time of the detector.

A preliminary estimate of the laser beam divergence has been made by photographing the laser spot at increasing distances away from the laser cavity. The beam divergence was found to be ~10 mrad. The observed low beam divergence compared to a geometrical divergence of nearly 60 mrad (for a 2-pass system) together with the fact that the cavity was very sensitive to alignment, indicates a multipass laser oscillation. For a laser pulsewidth of 8 ns and a cavity length of 12 cm, nearly 8 round trips would be possible.

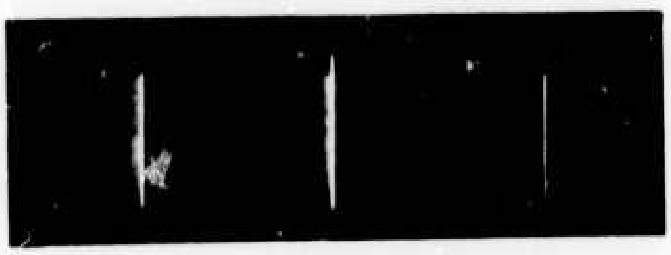
Assuming that a multipass laser oscillator has been achieved, an estimate of the saturated gain coefficient may be made from the following considerations. In a high gain medium, the fluorescence emission closest to the output coupler and proceeding toward the total reflector, would provide the most dominating influence for stimulated emission. Then the saturated gain coefficient is given by $e^{20\alpha} = \frac{1}{0.92 \times 0.05} \simeq 22$, or $\alpha \sim 15\%/\mathrm{cm}$.

A rough estimate of the efficiency can also be made on the basis of the absorbed E-beam energy. The stopping power of the ~100 psia Ar is approximately 16 kV/cm. The total energy absorbed by the 30 cm^3 volume during the lasing pulse (~12 ns) with a current density of 150A/cm^2 is calculated to be ~ 0.85J. Therefore the output of 4 mJ represents an efficiency of ~0.5%.

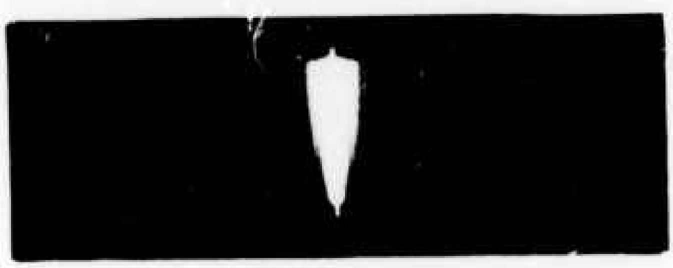
Figure 7 shows the results of the spectral study. The fluorescence spectrum of 16 atm N_2 showed three lines at 3371Å, 3577Å, and 3805Å. These lines belong to the transition $v' = 0$ of the $C^3\pi_u$ to the $v'' = 0, 1, 2$ of the $B^3\pi_g$ state of the N_2 molecule. The same three lines appear in the fluorescence spectrum of 16 atm Ar, 1 atm N_2 mixture, but with considerably higher intensity. This is a result of energy transfer as well as the reduction in



Fluorescence Spectrum of N_2 (15 atm)



Fluorescence Spectrum of Ar + N_2 (16:1 atm)



Laser Spectrum of Ar + N_2 (16:1 atm)

Figure 7. Fluorescence spectra of N_2, Ar + N_2 together with the laser spectrum.

N_2 self-quenching of the C state. The laser spectrum primarily consists of the 0-1 line at 3577Å. Photodiode measurements show that the other two lines are smaller in intensity by at least two orders of magnitude. Thus the spectral study provides further supporting evidence of the laser oscillations.

Laser output as a function of pressure at a constant E-beam current density was investigated, and the results are shown in Figure 8. The peak laser intensity is observed to decrease at pressures higher than 100 psia. The reason for this decrease is not yet clear, since it can occur due to a variety of causes: e.g., the decrease in effective current density at higher pressures, the reduction in gain by pressure broadening or even a higher rate of non-radiative losses. Investigations are now proceeding to study this and other parametric dependences in order to gain insight into the laser mechanisms.

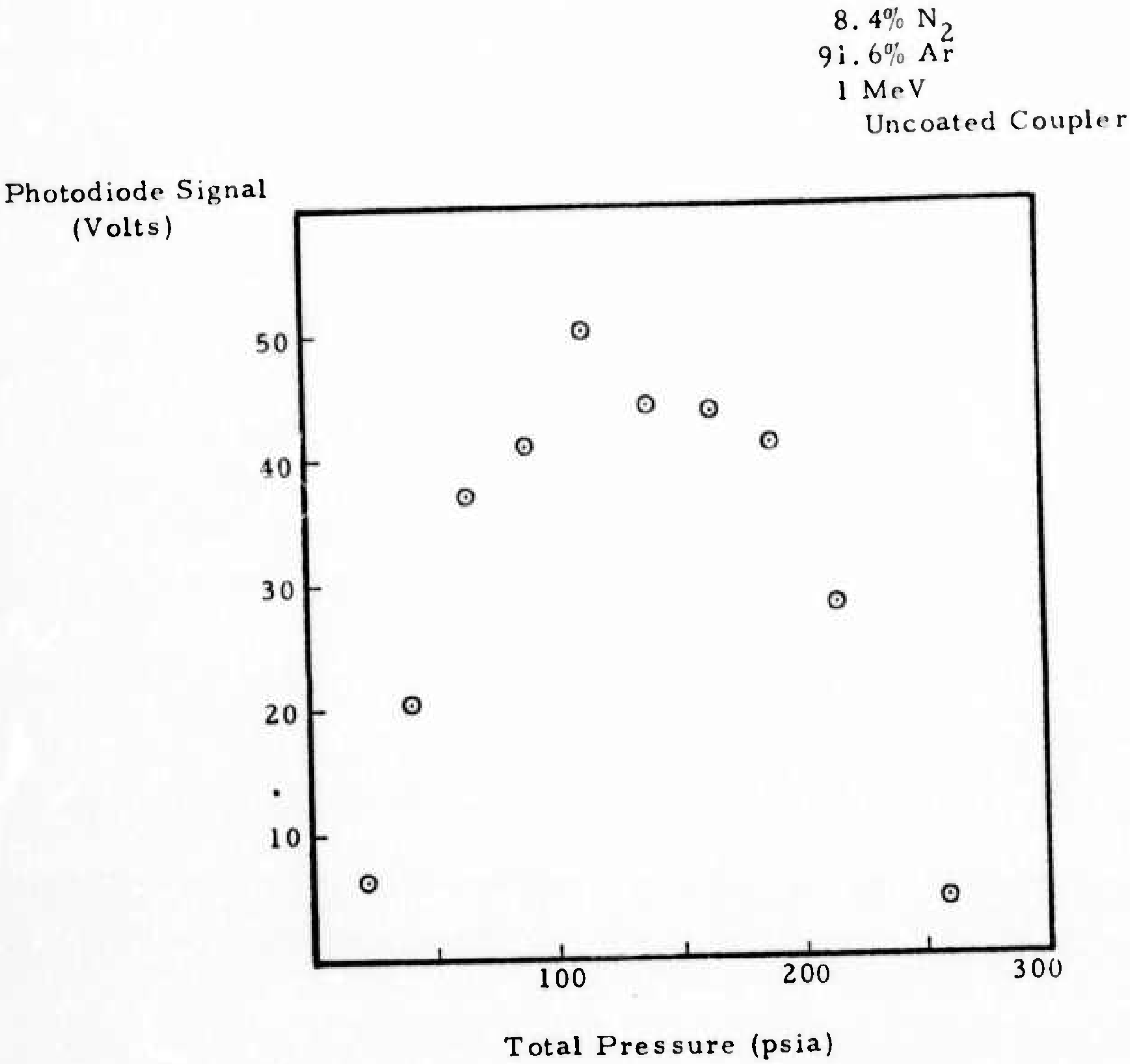


Figure 8. Pressure dependence of the laser peak power for a constant current density (~ 500A/cm^2) incident on the gas cell.

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6. S. K. Searles, private communication.

4.0 APPENDIX I

High Power Ar-N_2 Transfer Laser at 3577Å *

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ABSTRACT

A peak laser power of 0.5 MW with an estimated efficiency of 0.2% has been obtained at 3577Å from a mixture of 92 psia Ar and 8 psia N_2 which was excited by an E-beam of 400A/cm^2 at 1.3 MeV in a 20 ns pulse. A saturation intensity of ~100 kW/cm^2 was deduced and a beam divergence of 10 milliradian was measured from the laser having a 10 cm gain length.

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Paper accepted for publication in IEEE JQE

We report the observation of high power laser oscillations in the N_2 second positive band from high pressure gas mixtures of argon and nitrogen excited by a relativistic electron beam. The possibility of developing such a laser by utilizing the high electrical conversion efficiency of rare gases followed by nonradiative energy transfer to a suitable laser gas was suggested by Eckstrom, et al.[1] Based on this concept, an $Ar\text{-}N_2$ laser with an output of 10-100 watts has been reported by Searles.[2]

We have observed 8 nsec wide laser pulses, with peak powers as high as 0.5 MW from a mixture of 8% N_2 and 92% Ar at 7 atmospheres. The laser configuration and the diagnostic instrumentation are illustrated in Figure 1. The laser gas cell consisted of a 30 cm^3 volume (2 cm diameter by 10 cm long) sealed at each end with uncoated magnesium fluoride windows. The electron beam was injected into the gas cell transverse to the optical axis, through a 1 mil titanium foil window.

The optical cavity was defined by one of the uncoated magnesium fluoride gas cell windows and a 4 meter, 92% Al reflector mounted outside the second gas cell window. Because of the ~2.5% reflection at each surface of the magnesium fluoride windows, the front window constituted the output coupler with an approximate coupling of 95%. The mirror was aligned with the output coupler by means of a He-Ne laser and a beam splitter temporarily inserted into the optical cavity.

The electron gun used to excite the high pressure gas cell was a Physics International model Pulserad 110A. The current output of the gun was 20 kA at 1 MeV in a 20 ns pulse over an area of 2 cm x 10 cm. Although the maximum E-gun current density was nearly 1 kA/cm^2, the effective current density inside the gas cell, after traversing 4 mils of titanium (3 mil anode foil plus 1 mil gas cell foil) and 1 cm of air, was $400A/cm^2$ at the front of the gas cell and $200A/cm^2$ at the back. The current density, which is an important parameter in establishing the laser threshold, was varied by placing additional scattering foils between the E-gun anode foil and the gas cell. The diode voltage was also varied over the range of 1.3 to 1 MeV. Since the electron range is much larger than the dimensions of the gas cell (the electron beam energy loss in traversing the gas cell is ~32 keV at 100 psia and 1 MeV), small changes in the electron beam energy did not appreciably change the pumping rate.

The total pressure of three gas mixes (4%, 8% and 16% N_2 in Ar) was varied from 20 psia to 260 psia. The maximum optical output was obtained from a total pressure of 100 psia for the three N_2 partial pressures tested. Before filling the cavity with the N_2-Ar mix, it was evacuated with a diffusion pump to 2×10^{-5} torr. This procedure provided a means of maintaining the gas purity level to the 99.99% purity specification of the fill gas.

The laser diagnostics were primarily accomplished by intensity measurements with an ITT FW114A photodiode. The photodiode signal was measured with a Tektronix 7904 oscilloscope having a 500 MHz vertical amplifier. To

prevent the photodiode from saturating, the optical output was attenuated by diffuse scattering from a MgO surface, as illustrated in Figure 1. The gas cell current density was monitored, simultaneously with the optical intensity, by means of a Faraday probe mounted flush with the rear surface of the gas cell. Spectral measurements of the laser output were made with a SPEX 1800 1 meter Czerny-Turner spectrograph having a dispersion of 10Å/mm and the spectral output could be detected either by a photodiode or by recording on film.

Typical photodiode and Faraday probe signals from an excited gas mixture of 8% N_2 and 92% Ar at 100 psia are shown in Figure 2. The temporal narrowing of the optical pulse is evident from the figure, which shows an optical pulse of 8 ns FWHM with a rise time of 2 ns, while the E-beam current pulse is ~20 ns (FWHM) wide and rises in ~5 ns. The normal fluorescence pulse, not shown in the figure, follows the shape of the current pulse. The peak of the laser pulse occurred within ±3 ns of the peak of the current pulse. Further evidence of laser oscillation was obtained by measuring the optical intensity with the total reflector removed and by misaligning the cavity mirrors. In these tests the intensity decreased by at least two orders of magnitude and there was no temporal narrowing in either case.

The optical output showed the characteristic laser threshold as a function of electron beam current density. The results of such an experiment are given in Figure 3, which is a graph of the peak photodiode voltage versus the peak

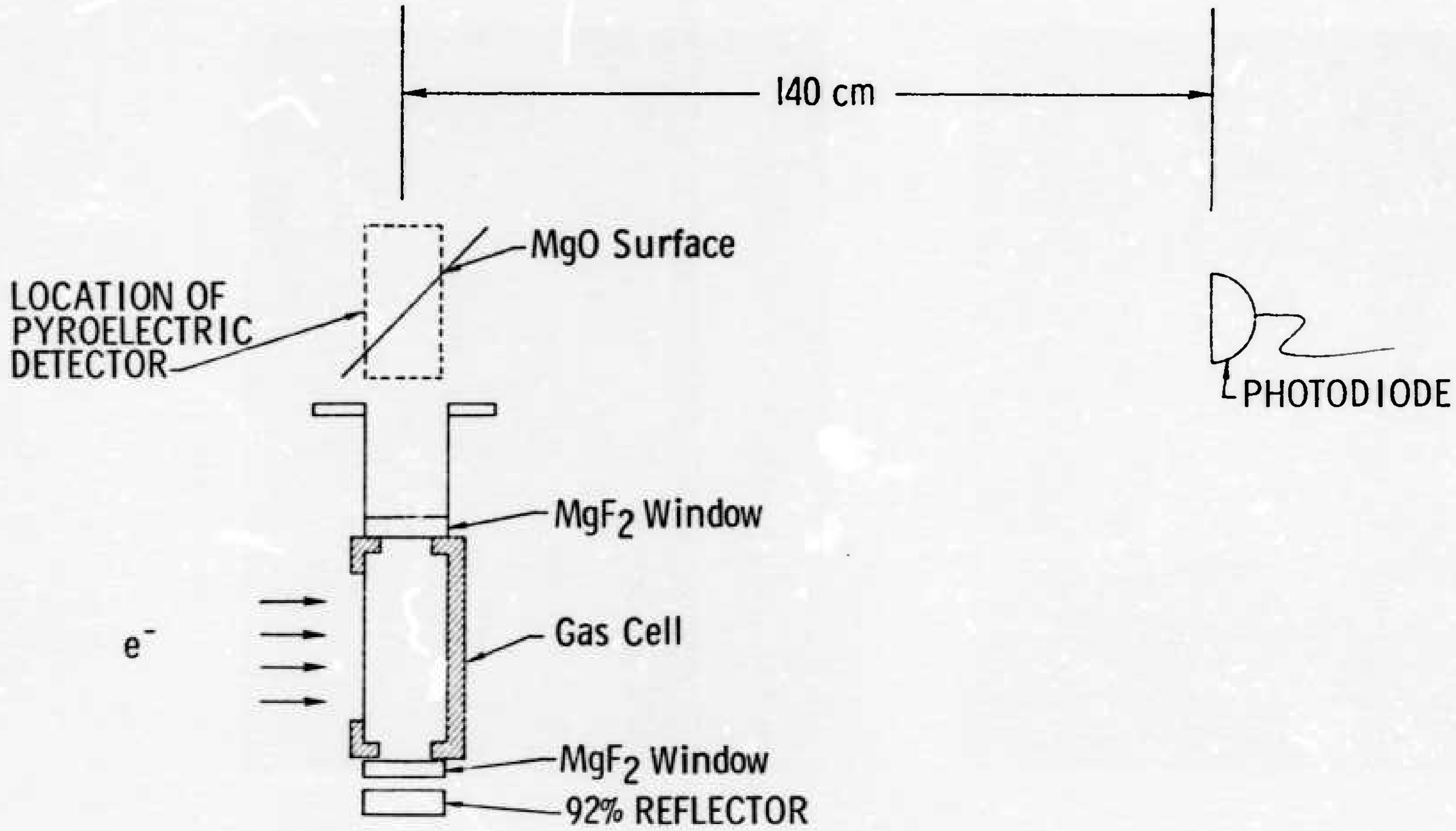
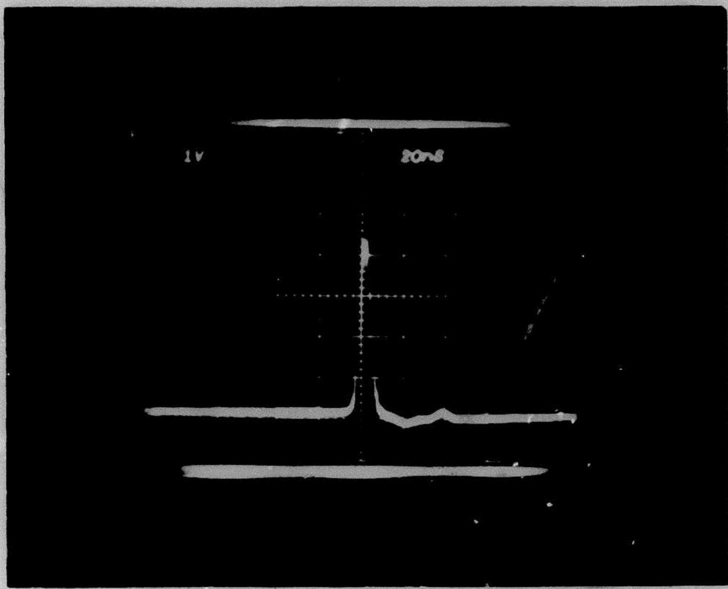
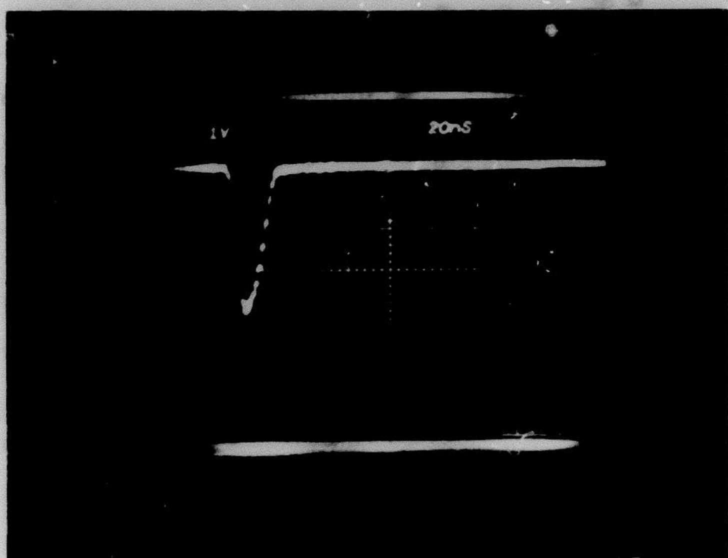


Figure 1. Schematic of the E-beam excited laser. For energy measurements, the MgO surface was replaced by an integrating pyroelectric calorimeter.



(a) PHOTODIODE OUTPUT



(b) FARADAY CUP SIGNAL

Figure 2. (a) Photodiode signal from Ar-N_2 laser (vertical scale 40 V/div.); (b) Faraday cup signal (5 amp/div.). Time scale for both traces is 20 ns/div. There is a cable delay of 70 ns between the two pulses.

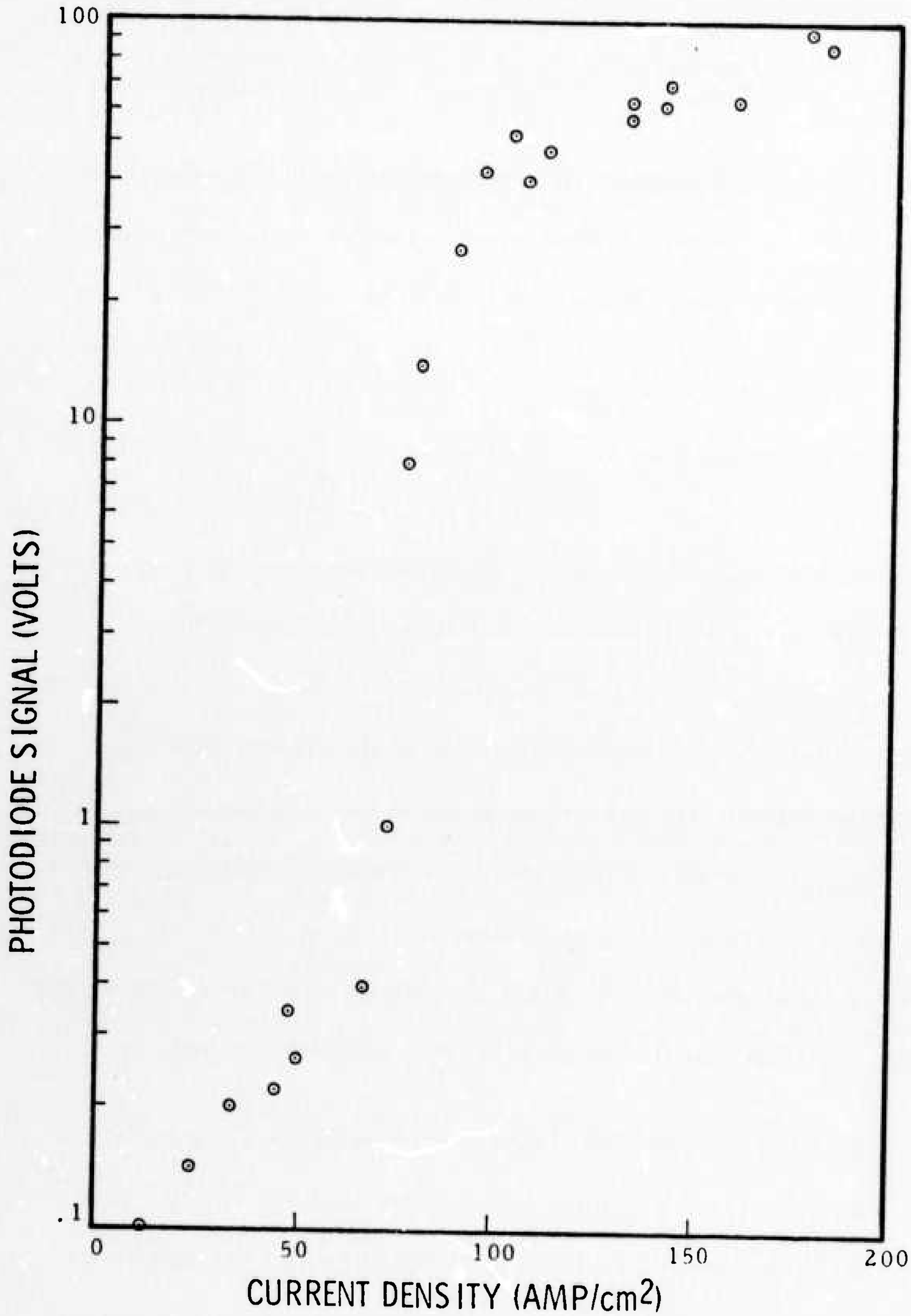


Figure 3. Peak photodiode voltage as a function of excitation current density showing laser threshold in a mixture of 92 psia Ar + 8 psia N_2.

Faraday probe current. Below threshold the optical output temporally follows the current pulse. However, as the current density is increased above threshold, there is temporal narrowing along with a substantial increase in the output intensity. As can be seen from the experimental results in Figure 3, the output intensity increases by two orders of magnitude when the electron beam current density is doubled.

The total energy output of the laser was measured by a Gentec model ED200 integrating pyroelectric detector. The highest energy measured was 4 mJ, which corresponds to a peak power of 500 kW for a pulse of 8 ns (FWHM). This peak power is consistent with the photodiode measurement after corrections to the geometric attenuation. At the knee in the threshold curve (Figure 3), the peak power is approximately 300 kW and above this point the laser output appears to be linearly dependent on the current density. With the 95% output coupler, the intracavity power at the output coupler is approximately equal to the output power so that the estimated saturation power is 300 kW, which corresponds to a saturation intensity of 100 kW/cm^2. This is considerably higher than the saturation intensity reported by Leonard[3] in a low pressure nitrogen laser operating in the second positive band.

Preliminary measurements of the laser beam divergence were made by exposing film at increasing distances away from the laser cavity. The measured beam divergence was 10 mrad compared with a potential geometrical divergence of 60 mrad for a 2-pass system. This fact together

with the observation that the laser output power was sensitive to the cavity alignment indicates multipass laser oscillation. For a laser pulsewidth of 8 ns and a cavity length of 12 cm, nearly 8 round trips are possible.

An estimate of the efficiency may also be made on the basis of the absorbed E-beam energy. The stopping power of the 100 psia Ar is approximately 16 kV/cm. The total energy absorbed by the 30 cm^3 volume during the electron beam pulse (15 ns FWHM) at an average current density of 300A/cm^2 is calculated to be 2 J. Therefore the output of 4 mJ represents an efficiency of ~ 0.2%.

The fluorescence spectrum of 16 atm N_2 showed three lines at 3371Å, 3577Å, and 3805Å. These lines belong to the transition $v' = 0$ of the $C\,^3\Pi_u$ to the $v'' = 0, 1, 2$ of the $B\,^3\Pi_g$ state of the N_2 molecule. The same three lines appeared in the fluorescence spectrum of 15 atm Ar, 1 atm N_2 mixture, but with considerably higher intensity. This is probably a result of energy transfer as well as the reduction in N_2 self quenching of the C state. The laser spectrum primarily consisted of the 0-1 line at 3577Å. Photodiode measurements showed that the other two lines were smaller in intensity by at least two orders of magnitude. Thus the spectral study provides further supporting evidence of laser oscillation.

Laser output as a function of pressure at a constant E-beam current density was also investigated. The peak laser intensity was observed to decrease at pressures higher than 100 psia. The reason for this decrease is not yet

clear, since it could occur due to a variety of causes: e.g., the decrease in effective current density at higher pressures due to scattering losses, the reduction in gain by pressure broadening or a higher rate of nonradiative losses. Investigations are now in progress to study this and other parametric dependences in order to gain insight into the laser mechanisms.

In summary, the experimental results presented above show clear evidence of strong laser oscillation from high pressure Ar-N_2 mixtures. A definite threshold is observed in addition to temporal narrowing and significant spectral changes. Once over threshold, the laser output is sensitive to optical alignment and the beam divergence is smaller than would be expected with a 1 or 2-pass system. This indicates that the laser was a true oscillator and not a superradiant emitter.

The authors wish to express their thanks to C. F. Zahnow and R. P. Ziesing for their assistance in carrying out these experiments.

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